Date: 8/8/01 Express Mail Label No. EL552579028US

Inventor: Felix A. Levinzon

Attorney's Docket No.: 1575.2003-001

HIGH AND LOW FREQUENCY BAND DUAL OUTPUT TRANSDUCER

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application No. 60/223,884, filed on August 9, 2000; the entire teachings of which are incorporated herein by reference.

BACKGROUND OF THE INVENTION

Transducers are devices used for converting energy from one form to another to measure a physical quantity. A typical transducer converts mechanical force or acceleration into electromagnetic energy. A transducer is mechanically coupled to an object to measure its motion. When this motion is vibrational, usually only certain frequency ranges are of interest. In such cases, the transducer must provide some means of filtering out the unwanted frequencies. To achieve this filtering, a transducer is normally composed of: (a) a sensor element providing an output signal with a broad frequency range and (b) an amplifying and filtering circuit that is electrically connected to the sensor element's output and eliminates the unwanted frequencies outside a given frequency band of interest.

Existing transducers are designed for sensing either low-frequency vibrations or high-frequency vibrations. To obtain signals representing both the low-frequency vibrations and high-frequency vibrations, two transducers must be used.

SUMMARY OF THE INVENTION

The principles of the present invention teach a transducer that can operate with a single sensor and an electronic circuit having two filtering circuits providing separate outputs. By combining at least two filtering functions into a single circuit that can convert a single sensor output into corresponding electrical signals, the transducer is reduced in size, weight, and cost, and provides improved performance for measurement systems where measurement of multiple frequency signals are needed. For example, the low-frequency, linear region of the sensor signal provides force or motion information, and the high, natural resonance frequency of the sensor signal can be used as a diagnostic signal or other status indicator.

One embodiment of the present invention accomplishes this task by using an innovative electronic circuit which converts a high-impedance, broad frequency range signal from a sensor into two low-impedance outputs. Typically, one output provides high-frequency signals and the other output provides low-frequency signals. The circuit may also amplify and/or offset the signal. Output signal offset can be used to put the signal within the delivery range needed by a system using the present invention and to establish a proper bias for electronic components to avoid clipping and saturation in their operation within an embodiment of the invention.

The low-frequency output signal can contain, for example, the frequency components corresponding to the linear part of the sensor's frequency response band, providing force or motion information. The high-frequency output signal can contain, for example, the frequency components corresponding to the natural resonance frequency of the sensor, which may be designed at a select frequency for high sensitivity based on the dynamics of the system being monitored for vibration. The high-frequency signal can be used as a diagnostic signal or other status indicator.

The sensor can be, for example, a piezoelectric (PE) sensor transforming a sensed force or mechanical vibration into a corresponding high-impedance electrical signal with a broad frequency range, where the transfer function is essentially linear with low hysteresis.

In one embodiment, the electronic circuit includes a low-frequency filter amplifier module and a high-frequency filter amplifier module. Both filter amplifier modules have high input impedance, low output impedance, and negative feedback. The negative feedback may be provided by respective single capacitors. The filter amplifier circuit outputs may be DC-biased to provide sufficient signal swing without clipping or saturating circuit components.

The electronic circuit may further include a buffer to isolate the filter amplifier modules from each other. In one embodiment, the buffer is electrically disposed between an input to the circuit and an input to the high-frequency filter amplifier module. In an alternate embodiment, the buffer is electrically disposed between the input to the circuit and an input to the low-frequency filter amplifier module.

The buffer can be implemented in the form of an operational amplifier arranged in a source follower configuration. The buffer may be unipolar, with one power rail receiving power from the output of the low-frequency filter amplifier module and the other power rail being connected to power return or ground. This arrangement has the advantage of not having to use separate power sources for the low- and high-frequency filter amplifier circuits and the buffer.

Because the low-frequency filter amplifier module's input is electrically connected directly to the sensor, a capacitor or an equivalent circuit can be electrically disposed between the buffer's output and the high-frequency filter amplifier module's input to ensure similar input impedances on the inputs of both filter amplifier modules.

In an alternative embodiment, the buffer is electrically disposed between the sensor and the low-frequency amplifier module. In this embodiment, a capacitor or an equivalent circuit providing a sensor-type output impedance can be electrically disposed between the buffer's output and the low-frequency filter amplifier module's input.

The circuit may include a variety of means aimed at eliminating noise and temperature dependence of the circuits' components and characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram of a transducer providing low- and high-frequency outputs according to the principles of the present invention;

Fig. 2 is an electrical schematic diagram of the transducer of Fig. 1;

Fig. 3 is a Bode plot of the calculated frequency responses for the low- and high-frequency outputs of the transducer of Fig. 2;

Fig. 4 is a Bode plot of a measured frequency response of the high-frequency output of the transducer of Fig. 2 at a temperature of 25 degrees Celsius;

Fig. 5 is a Bode plot of a measured frequency response of the high-frequency output of the transducer of Fig. 2 at a temperature of 120 degrees Celsius;

Fig. 6 is a Bode plot of a measured frequency response of the low-frequency output of the transducer of Fig. 2 at a temperature of 25 degrees Celsius;

Fig. 7 is a Bode plot of a measured frequency response of the low-frequency output of the transducer of Fig. 2 at a temperature of 120 degrees Celsius;

Fig. 8 is a Bode plot of a measured noise spectrum of the low-frequency output of the transducer of Fig. 2 at a temperature of 25 degrees Celsius; and

Fig. 9 is a Bode plot of a measured noise spectrum of the high-frequency output of the transducer of Fig 2 at a temperature of 25 degrees Celsius.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular description of preferred embodiments of the invention, as illustrated in the accompanying drawings in which like reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention.

DETAILED DESCRIPTION OF THE INVENTION

A description of preferred embodiments of the invention follows.

Fig. 1 is a block diagram of an embodiment of a transducer 13 according to the principles of the present invention. The transducer 13 comprises a sensor 1 and an

electronic circuit 12. The electronic circuit 12 includes a low-frequency channel circuit 2 and high-frequency channel circuit 4.

A high-impedance signal from the sensor 1 is processed by the low-frequency channel circuit 2 and high-frequency channel circuit 4. The low-frequency channel circuit 2 produces a DC-biased, low-impedance, low-frequency signal on a first output terminal 3; the high-frequency channel circuit 4 produces a DC-biased, low-impedance, high-frequency signal on a second output terminal 5.

The low-frequency channel circuit 2 includes a low-frequency filter amplifier 6 and a negative feedback path 7, which is composed of a single capacitor in this embodiment. The low-frequency filter amplifier 6 has a high input impedance and low output impedance.

The high-frequency channel circuit 4 includes a high-frequency filter amplifier 8 and a negative feedback path 9, which is also composed of a single capacitor in this embodiment. The high-frequency filter amplifier 8 has a high input impedance and low output impedance.

The electronic circuit 12 also includes a buffer 10, configured here as a source follower, which provides a high impedance (i.e., isolation) and eliminates cross-coupling between the high-frequency filter amplifier 8 and the low-frequency filter amplifier 6. In one embodiment, the voltage supply for the buffer 10 is provided by the DC-biased low-frequency output 3 so that the source follower 10 does not need its own power supply. The source follower 10 has a high input impedance and low output impedance.

The high-frequency channel circuit 4 receives the output of buffer 10 through a capacitor 11. The capacitor 11 ensures similar input impedances on the input of low-frequency filter amplifier 6, which is connected directly to the sensor 1, and on the input of high-frequency filter amplifier 8. The capacitor 11 also rejects low frequency variations on the output of the buffer 10 caused in part by using the output of the low-frequency output 3 of the low-frequency channel circuit 2 as a voltage supply for the buffer 10.

One use of the transducer 13 is in a motion sensing application in which the sensor 1 is a piezoelectric (PE) sensor detecting motion in a linear, low-hysteresis, high-sensitivity manner. In such applications, a high-frequency output signal of the sensor 1 includes a signal that is representative of the natural mechanical resonance frequency of the sensor 1, while a low-frequency output signal includes a frequency range of signals that are representative of signals within the frequency range corresponding to the linear, low-frequency motion of the sensor 1. Thus, a single sensor and single circuit can be provided by the present invention transducer 13 to provide motion information containing the low- and high-frequency signals simultaneously. Such information can presently be provided only by two separate sensors and circuits of prior art transducer systems. Thus, the size, weight, and cost of the motion sensing system is reduced and the performance is improved.

Fig. 2 is an electrical schematic diagram of an embodiment of the transducer 13. Before describing circuit specifics, correspondence between the schematic diagram of Fig. 2 and block diagram of Fig. 1 is provided.

The transducer 13 includes the sensor 1 and electronic circuit 12. The electronic circuit 12 includes low-frequency channel circuit 2, high-frequency channel circuit 4, and buffer 10.

The low-frequency channel circuit 2 includes a low-frequency channel input terminal T1 and low-frequency channel output terminal T2. Similarly, the high-frequency channel circuit 4 includes a high-frequency channel input terminal T3 and high-frequency channel output terminal T4.

The buffer 10 is implemented as a unity gain source follower through the use of an operational amplifier U1. The buffer 10 receives power from the low-frequency channel output terminal T2 and power return (i.e., ground) 0.

While the schematic diagram of Fig. 2 is believed sufficient to make the properties of the transducer 13 apparent to a person skilled in the pertinent field, some details and features of the transducer are specifically pointed out.

The n-channel JFET transistor J6 amplifies the input signal on its gate, reduces the output noise, and ensures the high input impedance for the low-frequency filter amplifier 6. The n-channel JFET transistor J8 provides the same features for the high-frequency filter amplifier 8.

The p-n-p transistor Q8, together with the resistors R11, R14, R15, and R16 and the capacitors C5 and C6, provide a proper biasing and reduce the noise on the gate of the JFET transistor J6 in the low-frequency filter amplifier 6.

The p-n-p transistor Q1, together with the resistors R2, R6, R7, and R8 and the capacitors C11 and C14, provide a proper biasing and reduce the noise on the gate of JFET transistor J8 in the high-frequency filter amplifier 8.

The p-n-p Darlington transistor Q7 ensures the low output impedance of the low-frequency filter amplifier 6; its emitter and collector are connected to the output wires of the low-frequency filter amplifier 6. The n-channel JFET transistor J5 ensures the proper regime for the Darlington transistor Q7. The p-n-p Darlington transistor Q3 and the n-channel JFET transistor J7 provide the same features for the high-frequency filter amplifier 8.

In the low-frequency filter amplifier 6, the n-channel JFET transistors J3 and J4, connected as diodes in series between the ground 0 and the channel of the JFET transistor J6, provide the voltage offset for the JFET transistor J6 and also reduce the temperature dependence of its operation. The n-channel JFET transistors J1 and J2 provide the same features for the JFET transistor J8 in the high-frequency filter amplifier 8.

In the low-frequency filter amplifier 6, the capacitors C1, C2, and C7 together with the resistors R12 and R13 function as a two-pole, low-pass filter with the frequency range (-3dB) of about 1.5 Hz to 8 kHz; the capacitor C10 functions as the negative feedback 7. The resistor R11 together with the capacitor C10 function as a one-pole high-pass filter with the frequency cutoff (-3dB) of about 1.5 Hz, for the low-frequency filter amplifier 6. The resistors R3 and R4 together with the capacitor C9

function as a one-pole low-pass pre-filter with the frequency cutoff (-3dB) of about 460 Hz, for the low-frequency filter amplifier 6.

In the high-frequency filter amplifier 8, the capacitors C16 and C12 together with the resistors R22 and R5 function as a two-pole high-pass filter with the frequency range (-3dB) of about 19 kHz to 52 kHz; the capacitor C16 also functions as the negative feedback 9. The resistor R1 together with the capacitor C4 function as a one-pole low-pass pre-filter with the frequency cutoff (-3dB) of about 80 kHz, for the high-frequency filter amplifier 8.

In the embodiment of Fig. 2, the values and configuration of the components involved in filtering signals within the transducer 13 are designed according to the principles of filter design commonly known in electrical engineering and similar arts and described, for example, in Adel S. Sedra & Kenneth C. Smith, Microelectronic Circuits 787-89, 792-93 (2d ed. 1987). Alternatively, active filter design principles may be used for both the low-frequency filter amplifier 6 and high-frequency filter amplifier 8 as well as for pre-filtering of an input signal. An active or passive biquad filter design can be used.

The capacitor C4 on Fig. 2 corresponds to the capacitor 11 on Fig. 1. Its function is to establish on the input of the high-frequency filter amplifier 8 the input characteristics similar to those provided by the sensor S on the input of the low-frequency filter amplifier 6. To achieve this, the characteristics of capacitor C4 should be similar to the characteristics of the sensor's capacitance, represented in Fig. 2 as C3.

The capacitor C15 provides additional DC decoupling between the input and output of the high-frequency filter amplifier 8.

The operational amplifier U1 is configured as a source follower and functions as the buffer 10. The resistors R17, R10, and R21 establish the proper input offset, and the capacitor C8 provides DC decoupling for the input of the buffer 10. The power for the operational amplifier U1 is provided by the output of the low-frequency filter amplifier 6.

The low-frequency filter amplifier 6 has a two-wires output and, therefore, includes both the voltage source V2 (24 V DC) and the current source I1 (4 mA). The voltage source V1 and current source I2 provide the same functions for the high-frequency filter amplifier 8.

In the transducer shown in Fig. 2, each output T2, T4 provides the same sensor gain of 2 mV/pC and the same maximum output swing of 5V. For a 50 pC/g sensor, each output provides the same sensor sensitivity of 100 mV/g.

Fig. 3 is a Bode plot of magnitude responses of the low-frequency channel circuit 2 and the high-frequency channel circuit 4 for the embodiment of the transducer 13 shown in Fig. 2. The Bode plot is representative of the low- and high-frequency outputs of the transducer 13 when the sensor input to the circuit 12 is a swept sine wave having an amplitude of 1 volt. The Bode plot was obtained by simulating the circuit of Fig. 2 using ORCAD®, a standard electronics design and simulation software program. The units of the horizontal logarithmic axis are frequency. The vertical linear axis is showing magnitude of the output in volts.

A circuit embodying the schematic circuit of Fig. 2 was implemented on a breadboard and its frequency response was tested at room temperature (25 degrees Celsius) and elevated temperature (120 degrees Celsius). This test yielded practically the same results as were obtained by computer simulations. Figs. 4, 5, 6, and 7 are sinesweep plots of that breadboarded circuit and have the same axes as the Bode plot of Fig. 3 for comparison purposes.

Fig. 4 is a Bode plot of a measured frequency response of the high-frequency output of the implementation of the transducer of Fig. 2 at the temperature of 25 degrees Celsius. For the reference frequency of 27.38 kHz, the -3dB points are measured to be 18.7 kHz and 52.8 kHz as expected for the two-pole high-pass filter configuration discussed above and shown on Fig. 2.

Fig. 5 is a Bode plot of a measured frequency response of the high-frequency output of the implementation of the transducer of Fig. 2 at the temperature of 120 degrees Celsius.

Fig. 6 is a Bode plot of a measured frequency response of the low-frequency output of the implementation of the transducer of Fig. 2 at the temperature of 25 degrees Celsius. For the reference frequency of 100 Hz, the -3dB points are measured to be 1.3 Hz and 9.07 kHz as expected for the two-pole low-pass filter configuration discussed above and shown on Fig. 2.

Fig. 7 is a Bode plot of a measured frequency response of the low-frequency output of the implementation of the transducer of Fig. 2 at the temperature of 120 degrees Celsius.

Results from the simulation and measured response of the breadboard circuit implementing the transducer shown on Fig. 2 indicate that the maximum deviation of the gain is about 6% and the bias deviation is about 2 volts DC in the temperature range of 25-120 degrees Celsius.

The following table provides approximate performance specifications for the implementation of the transducer of Fig. 2. These are exemplary specifications for a particular embodiment provided for illustrative purposes and not intended to limit the principles of the present invention.

Source capacitance	1000 pC ± 10%
Output impedance	10 ohms
DC output bias (over the temperature range)	8-13 V DC
Maximum output voltage	5 V peak
Frequency response for the LF output (100 Hz reference)	10%: 3 Hz - 5 kHz
Frequency response for the LF output (100 Hz reference)	-3 dB: 1.5 Hz - 8 kHz
Frequency response for the HF output (27 kHz reference)	-3 dB: 19 kHz - 52 kHz
Gain (each channel)	2 mV/pC
Residual noise for the LF output (2 Hz to 20 kHz)	25 μV rms typical
Residual noise for the HF output (2 Hz to 100 kHz)	22 μV rms typical
Warm-up time	5 sec
Power requirements	Powered from positive constant current source

Supply voltage	22 to 30 V DC
Supply current (for each channel)	4 mA nominal, 2 to 10 mA operating range
Operating temperature	-50°C to +120°C (-58°F to +248°F)
Non-operating temperature	-73°C to +150°C (-100°F to+302°F)

In the Bode plots of Figs. 8 and 9, the units of the horizontal logarithmic axis is frequency and units of the vertical linear axis is the voltage spectral density. The measurements were taken at a temperature of 25 degrees Celsius with the input of the circuit connected to ground 0, i.e. with the grounded input, where the sensor behaves essentially as a 1050 pF capacitor.

Fig. 8 is a Bode plot of a grounded-input noise response spectrum measured at the output of the low-frequency channel circuit 2 of the implementation of the transducer 13 of Fig. 2 at a temperature of 25 degrees Celsius.

Fig. 9 is a Bode plot of a grounded-input noise response spectrum measured at the output of the high-frequency channel circuit 4 of the implementation of the transducer 13 of Fig. 2 at a temperature of 25 degrees Celsius.

The noise measurements represented by the plots of Figs. 8 and 9 show the values of a noise spectrum that are practically identical to such values specified for traditional transducers. Thus, the noise measurements provide confidence that there is little cross-coupling between the low-frequency channel 2 and high-frequency channel 4.

While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

The transducer 13 can be implemented, for example, using surface mount technology or chip and wire technology. The analog circuits described herein can be implemented in digital circuitry or signal processing technology. It should be understood that typical techniques of conversion of filters from analog to digital form

can be used to implement in digital form the filtering features of the analog circuits described herein. For a digital processing implementation, analog-to-digital and digital-to-analog converters to sample and output the processed signal, respectively, can be used. Further, supporting analog circuitry, such as the buffer 10 and Nyquist filters, may be employed in the digital embodiment.